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VII.—*On the Molecular Formation of Crystals.* By ROBERT T. FORSTER, A.M.

Read May 14, 1855.

ALL the theories which have been advanced to account for the phenomena of crystallization have been, with one exception, but short-lived; and indeed it may safely be doubted if any occupy such a position as to entitle them to much credit.

The subject is one of much interest; and although the consideration that so many able minds have failed in the attempt to investigate it may naturally deter an inquirer, still, the prize is sufficient to persuade him to hazard the attempt.

I shall first take a short review of the many theories which have been advanced in explanation of the phenomena, and I trust I shall be able to show that some were unquestionably faulty, and all undoubtedly and confessedly deficient.

Passing by the many absurd theories advanced on the subject in ancient times, the first whom we find deserving of notice is CHRISTIAN HUYGENS. In his celebrated work on Double Refraction he considered the crystals of Iceland spar to be built up of spheroids, which, by their unequal density, separated the incident light into two rays. He did not, however, show why the spheroids are so aggregated.

Such was the germ of a theory which, in the hands of WOLLASTON, BREWSTER, and DANA, has obtained some status. None of these writers, however, have taken the smallest account of cleavage, a phenomenon which is certainly the most remarkable in the whole of crystallography, and which was the origin

and basis of the theory of HAÜY. We shall presently prove how his theory also signally failed.

The theory of HUGENS only applied to the third system; but the construction of crystals in the first follows as an easy consequence from it. (In order to avoid error, it is necessary to state that the systems and names made use of are those of ROSE.)

HOOKE, in his "Micrographia," advanced a similar hypothesis, except that he considered the atoms to be spherical—a supposition which would have accounted for forms in the first or regular system, but which would have utterly failed in case of the third, or rhombohedral, to which he applied it: nor does he perceive that the molecules, if left to themselves, would not assume a definite arrangement. He does not seem to consider these spheres as the ultimate atoms: he says that, having already shown how a fluid will naturally assume the spherical form, he will proceed to show how these spheres will unite to form a crystal. His experience, in common with many old writers, seems to have been confined to crystals of quartz;—in fact, some of them went so far as to think that everything crystallized in virtue of the quartz it contained.

The next who commanded attention was M. PRECHTL DE BRUN, whose ideas were, to a certain extent, the same as those of HOOKE, inasmuch as he considered a fluid to be made up of soft molecules; but he also considered, that while the body was undergoing its change of state, they suffered a change of form; and that under different degrees of pressure different crystals were produced.

Dr. WOLLASTON has fully demonstrated that this theory is totally erroneous in a mathematical point of view. Dr. WOLLASTON also, in the same article, which is published in the "Philosophical Transactions," propounded a theory to account for the formation of the ordinary octahedron and tetrahedron. He considered the molecules to be simply spheres mutually attracting each other, and he stated that such molecules will combine, as shown in Fig. 3, and thus form a tetrahedron. This, however, is certainly not the case; for if we consider the first spherical atoms which unite to form the crystal, it is evident that the first four will assume the form shown in Fig. 1; and a fifth atom will attach itself, as shown in Fig. 2, that being evidently the position of equilibrium; but if we examine Fig. 3, we find that any five adjacent spheres occupy such posi-

PLATE XI.

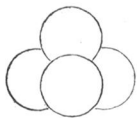


Fig. 1.

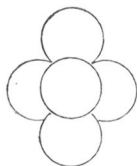


Fig. 2.

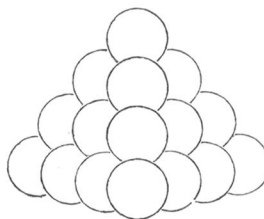


Fig. 3.

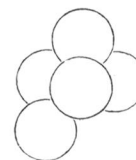


Fig. 4.

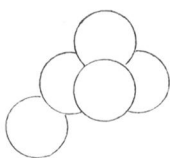


Fig. 5.

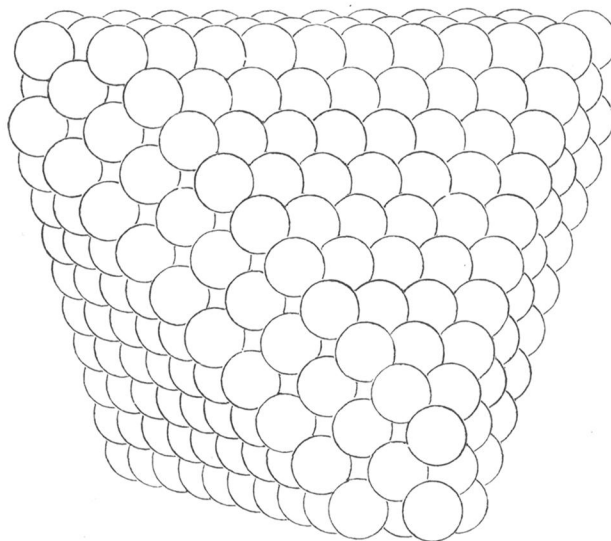


Fig. 11.

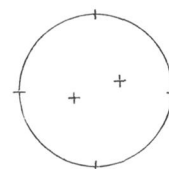


Fig. 6.

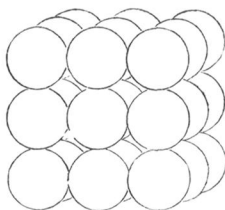


Fig. 7.

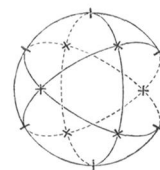


Fig. 8.

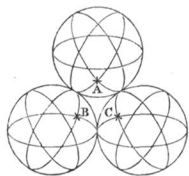


Fig. 9.

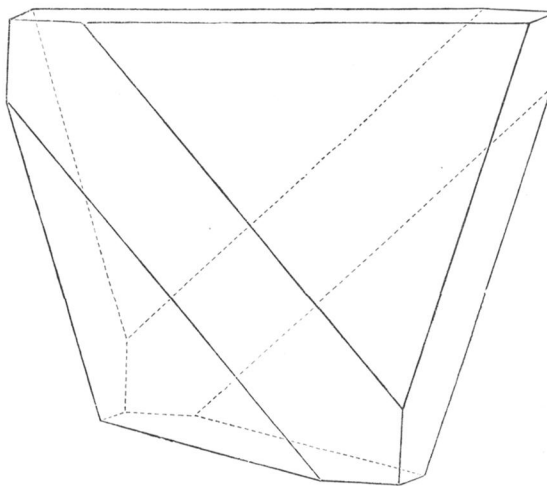


Fig. 12.



Fig. 10.

tions as shown in Fig. 4, or such as shown in Fig. 5, neither of which are positions of equilibrium.

WOLLASTON himself seems to have some lurking doubts of the validity of this assumption, as he begins by showing how the particles will become aggregated *if on a plane*, and then from this basis builds up the tetrahedron: this, however, is the very way in which crystals do not form.

The octahedron, of course, was easily deduced by removing the corners of the tetrahedron. He also formed the rhombohedron, by placing a pyramid of spheres on two opposite faces of the octahedron, and accounted for the different rhombohedrons by considering the spheres to become spheroids. He did not perceive that the planes of cleavage would in such a case be four in number; nor is it to be supposed that he would have advanced such an hypothesis if he had been acquainted with the theory of HUYGENS, which not only accounts for this form, but is in strict accordance with the known phenomena of cleavage. He also makes some observations with regard to the cube, but they are vague and indefinite, and indeed cannot be said to be a theory at all.

Next in order of time, and first in merit, was the Abbe HAÜY. His theory, as we have already stated, had its origin and groundwork in the phenomena of cleavage. His great merit lies in being the first to advance the theory of decrements, which is, perhaps, one of the most successful in the whole range of physical science. He perceived that many crystals were liable to cleavage, and that in many cases new solids were thus obtained: he was led from this to consider, that if this cleavage were continued long enough, we should ultimately arrive at the element itself; and he assumed, without sufficient foundation, that this element should have the same form with the solid obtained by cleavage. This element itself he considered to be further divisible into what he called the absolute atom.

The forms which he considered these elements or nuclei to have were the tetrahedron, parallelopiped, and the three-sided prism. With these he clearly accounted for nearly all primary forms; and by means of his theory of decrements ably included the secondary: but in case of the tetrahedral cleavage, his theory signally failed, for no one solid can be obtained by this cleavage, inasmuch as tetrahedra will not, however united, fill space. The only way in which this difficulty could be got over was by supposing that the tetrahedral

molecules were united by their corners, or that the crystal was formed of tetrahedral and octahedral molecules mixed. The necessity for such an arrangement, so unaccountable, and so totally at variance with the rest of his theory, was evidently subversive of it.

However easy it may be to divide a crystal into any number of molecules, it is by no means so easy to build up a crystal of these molecules;—in fact, he does not seem to have considered the problem as a physical one, nor to have investigated at all how the molecules could have united. To any one viewing the question in such a light, the difficulties of showing how such molecules could come together would appear insurmountable, if not subversive of the theory which gave them birth. No such difficulties exist, however, when we consider the atoms spherical, and attached to each other by means of poles, or centres of force: we can then begin with the individual atom, and trace it as it becomes part of a crystal, and as other atoms become attached to it.

Such is the system of Mr. DANA, the American mineralogist. To him belongs the merit of clearly pointing out how some hemitrope crystals occur. The first idea, however, undoubtedly originated with Sir DAVID BREWSTER, who stated the fact without explaining it. To give a detailed account of this theory is not my intention: suffice it to say, that the completeness and beauty of this part of it carry with them an irresistible conviction of its truth, so far as it goes, resembling in this respect the theory of decrements of HAÜY, which, despite the errors of his system, still remains, and applies where the particles are supposed to be spheres as well as where they are supposed to be cubes or tetrahedrons.

DANA considered the particles to be spheres or ellipsoids, possessing six poles or centres of force on their surface: three of these poles were of one name, and three opposite of another—those of a like name repelling, those of an unlike attracting each other. He explained the formation of twin crystals by showing how two molecules may unite at a point intermediate between two or three poles.

In Fig. 6 is shown the arrangement which he supposed the poles to have; the intersection of the circles shows their position; and in Fig. 7 the form into which the molecules will pile themselves. This was the only primitive form which he supposed to exist in the first system; and accordingly, he left quite

unexplained the different cleavages which are found ;—in fact, he took no notice whatever of cleavage, except some unintelligible remarks, and did not even perceive that this formation would give rise to the cubical cleavage, and no other,—a fact which we shall presently prove.

Thus we have the two most successful systems, those of HAÜY and DANA ; the first founded on the phenomena of cleavage, an attempt which, as we have seen, totally failed : the second altogether throwing aside the consideration of what is the most important and remarkable of all the phenomena of crystallization. The success of HAÜY's theory of decrements depends solely on the fact, that what he applied to cubes is equally applicable to spheres ; but it is to be remarked, that it would have completely failed if he had attempted to apply it to the other forms of molecules which he supposed to exist—in other words, his own theory failed completely when applied to his own system. We can only ascribe to a fortuitous circumstance the truth of a theory which has its very foundation in error.

DANA, however, was right so far as he went, and his theory will actually go a little farther than even he took it, for the formation which he supposed to exist will explain the cubical cleavage. The phenomenon of cleavage is a very remarkable one, and it may be said that the existence of several directions in which the crystal divides with less than the ordinary resistance is the origin of this phenomenon. It is evident that in any crystal where the faces are plane, and the molecules accordingly arranged in layers, the direction of that division which will give the least resistance will be some plane, and that this plane will be symmetrically situated with regard to the crystal, and that there will be as many planes as there are corresponding parts of the crystal, provided the poles of each molecule have the same attractive power. Thus, in the first system, where all the poles are naturally of the same strength, the number of planes of cleavage is either three, four, or six ; so, if a cube be divided by planes parallel to the faces, the number of different directions in which it will be divided is evidently three : if it be divided by planes tangential to an edge, as the edges are twelve in number, parallel two and two, the number of cleavage planes will evidently be six ; and if by planes replacing the corners, since the corners are eight in number, the cleavage planes are in number four. In order, then, to ascertain what will be the cleavage in any formation, we must look for

a plane where the cohesion is least, or, in other words, for a direction of least resistance. In DANA's formation (Fig. 7), it is evident that any division parallel to a face will separate each molecule from one other only, or, in other words, will overcome the cohesion of one pole in each molecule, while a division in a plane replacing an edge would separate each molecule from two others; and in a plane replacing a corner, from three others. The plane parallel to a face is evidently, then, the direction of least resistance, and will be the direction of cleavage. But there are two other cleavages—the very two to which we have been alluding—namely, tangential to the edges of the cube, and truncating the corners, which we shall for the future call the dodecahedral and octahedral cleavages, and which we shall now endeavour to explain.

If the molecules be spheres, each having twelve poles, or centres of force, on its surface, the form which they will assume is the tetrahedron. Such a molecule is shown in Fig. 8. The intersection of the great circles shows the positions of the poles: these poles evidently lie six and six on great circles: these circles are four in number, inclined to each other at the same angle as the faces of the tetrahedron ($70^{\circ} 31' 44''$), and are evidently divided each by the others into segments of 60° . The arrangement of the poles is perfectly symmetrical. For if any two of these spheres become united by two of their poles, they will assume such a position as shown in Fig. 9, that is, the relative positions of all the poles will be the same in consequence of their mutual attraction: if they become attached in any other position, they will rotate round a common axis till they occupy that position: a third will unite itself, as shown in Fig. 9, for the very same reasons; while a fourth would attach itself by its three poles, A', B', C' , (Fig. 10) to the three poles A, B, C ; for, since all the arcs joining these poles are 60° , these poles are the very points at which the spheres touch each other. We have now a tetrahedron formed, and by precisely analogous reasoning we can continue the process of formation.

It will be observed that a fifth molecule, if attached, will be in a plane with three others, and will only touch two, a result to the necessity of which I have already adverted when speaking of Dr. WOLLASTON's hypothesis.

We have seen how a tetrahedron may be formed: we will now investigate how it may be modified.

If a row of molecules along each edge is deficient in each consecutive layer,

planes will appear replacing the edges tangentially (*vide* Fig. 11). This can be readily demonstrated.

The face thus formed will belong to the cube. In Fig. 12 we have a representation of the crystal so produced; it is the same as that in Fig. 11. We have now seen that the union of the cube with the tetrahedron follows as a natural consequence from our hypothesis of twelve poles; but it would not be at all so easy to see, on the hypothesis of six poles, how four corners of a cube can be modified, and not the remaining four;—in fact, it would be directly contradictory to the laws of symmetry. We have already seen that the hypothesis of six poles explains the cubical cleavage; but it is a fact that *no crystal possessed of cubical cleavage exhibits the tetrahedral form, or that of any of its derivatives*. We have, hence, a striking confirmation of our hypothesis. In precisely analogous ways we can deduce the octahedron, the dodecahedron, the ikositetrahedron—in fact, every form of the first system, except hemihedral forms with parallel faces, namely, the pentagonal dodecahedron and the hemioctakisexahedron; but it is well known that *these two forms are never found in combination with the tetrahedron, or any other hemihedral form without parallel faces*. Here is another fact which gives the strongest support to our theory. We thus meet with two remarkable and isolated exceptions, which, viewed as matters of experiment, are sufficiently singular, but which follow as a beautiful and natural result of theory.

We have already seen that in case of the cubical formation, where the poles are six in number, the cleavage is parallel to the faces. We have shown that there will always be some *plane* of cleavage, and that it will always be the direction of least resistance. But in the case of twelve poles, in the tetrahedral formation before us, it is easily seen that the cleavage is again parallel to the faces; for there are only two possible planes of cleavage, namely, parallel to the faces and tangential to the edges; but cleavage parallel to the faces evidently separates each molecule from three others; while cleavage tangential to the edges separates each from four others: the former is, of course, that of least resistance.

We will now show how spherical molecules may assume the form of the dodecahedron, and will then proceed to prove that this formation will give rise to the dodecahedral cleavage.

If each sphere have eight poles, situated in the same relative positions as the corners of the cube, they will, if under no disturbing influence, assume the form of the dodecahedron ; for if any sphere attract eight others, they will be arranged as shown in Fig. 13 ; that is, their centres will occupy the same positions as the corners of a cube, but also their poles will all have the same positions as regards the eye, for their mutual actions will cause the spheres to turn on the points of mutual contact till they have such an arrangement. These eight will be attached simultaneously, and immediately six others will become attached to them, as shown in Fig. 14. It is evident that as the crystal grows, the same form is retained (Fig. 15). Such a crystal will be liable to modification in the same manner as those already discussed, and thus all forms may be built up. With regard to the cleavage of such a crystal, it is easily deduced by referring to the principles already made use of. The three possible planes of division in this formation are planes replacing an angle, replacing an edge, and parallel to a face. It is evident that the last is the natural one, for it separates each particle from two others, while that replacing an edge divides each particle from three ; that replacing an angle, from four others.

We have now reviewed all the forms of the first system, and have endeavoured to show under what circumstances the different cleavages will take place.

We have now to consider the other systems. As I have already said, DANA has shown how the forms in these systems will arise from the molecules being spheroids or ellipsoids, the length of whose axes and the position of whose poles are in every case given by the length and obliquity of the axes of the crystal ; but, as in the case of the first system, he has given but one formation for each of the other systems. We have already seen that this leaves unexplained the cleavage in the first, and the same is true for the others also. He considers the molecule in the second or dimetric system to be an ellipsoid of revolution with six poles, as in the first system. This will easily explain the prismatic and basal cleavages, but it will not account for the octahedral.

It is to be remarked, that in this, and every system except the first, we cannot expect that any poles will have the same strength except those of the same kind. We find, accordingly, that from the inferior strength of two of the poles, cleavage will exist in one direction only, or, as is often the case, may be

PLATE XII.

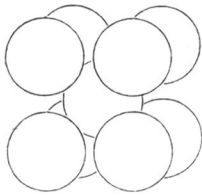


Fig. 13.

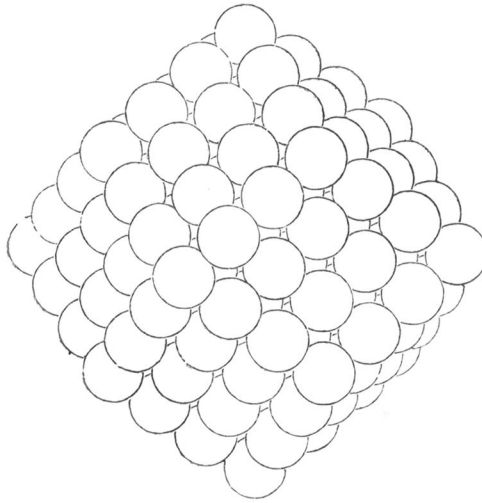


Fig. 15.

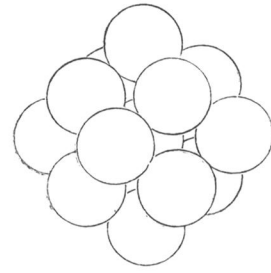


Fig. 14.

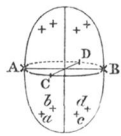


Fig. 16.

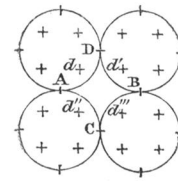


Fig. 17.

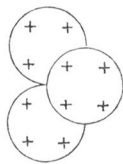


Fig. 18.

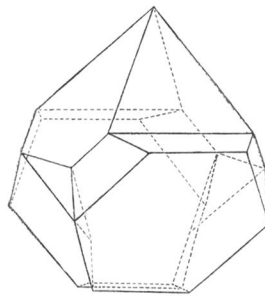


Fig. 19.

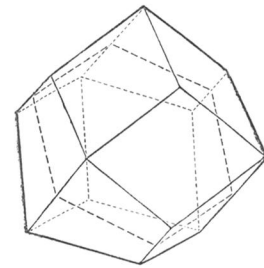


Fig. 20.

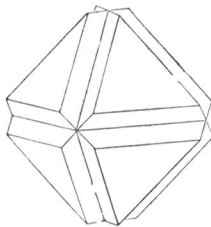


Fig. 21.

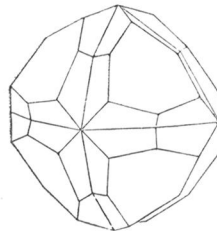


Fig. 22.

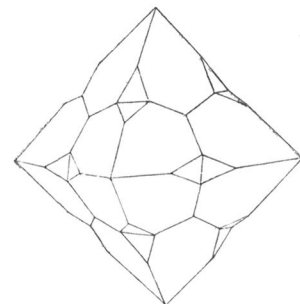


Fig. 23.

eminent. Thus, in the second system, we have cleavage parallel to the terminal plane only, because the poles at the extremities of the longer axes are the weakest : we have also cleavage parallel to the faces of the prism. When the contrary is the case, both these cleavages occur when the poles are six in number : but we have seen that the octahedral formation occurs in the first system when the poles are twelve in number ; and it is easily seen that it will also occur in the second system under similar circumstances.

The arrangement of the poles is shown in Fig. 16 : the poles, as in Fig. 8, lie six and six on ellipses which are four in number, and inclined to each other at the same angles as the faces of the octahedron which they unite to form. If any number of such ellipsoids unite by the poles A, B, C, D, they will be disposed as shown in Fig. 17, which is a section in the plane of these poles : another ellipsoid will become attached by its terminal poles (a, b, c, d) to the four poles d, d', d'', d''' : another will be attached opposite to it, and thus an octahedron will be formed. It is easily seen that the cleavage will be parallel to the faces of the octahedron ; for, as in the formation of the first system, that cleavage will separate each molecule from three others ; while the prismatic cleavage would separate each from four others. The poles are also of the same kind, taken in this manner, three and three, and accordingly all the cleavages will take place with the same facility.

It is evident that the tetrahedron will also be formed in the same manner.

We thus see that four molecules may first unite, as in Fig. 17, or three, as in Fig. 18, it being merely a matter of accident which result takes place. We have in the first case proved that the resulting form is the octahedron, and in the second the tetrahedron : thus we have a simple explanation of a fact which at first sight appears singular, that under the very same conditions we may have either the holohedral or the hemihedral form.

Thus we may have the tetrahedron of the second system ; and by means of decrements we can readily explain the dioctahedron and hemidioctahedron.

In the third, or rhombohedral system, the rhombohedron will be formed, if the molecule be an ellipsoid of revolution, and the poles are placed at the extremities of three equal conjugate diameters. This DANA has explained. The rhombohedral *cleavage* will also take place under similar circumstances ; but we have two other cleavages, namely, that parallel to the faces of the hexagonal prism, and that parallel to the base of the prism ; and these will evi-

dently occur if the molecules have eight poles—two at the extremities of the principal axis of the molecule, and six round the circumference of a circular section through its centre. If these six poles are stronger than the two others, the cleavage will be basal; if not, lateral; and if they all have the same strength, both cleavages will coexist.

We have thus shown how the primary forms of the rhombohedral system may be produced. The secondary forms can, of course, be explained on the same views. Thus, the dodecahedron can be easily deduced by means of decrements from either the rhombohedron or the hexagonal prism; and thus it may have either cleavage, and may be found in combination with either of these forms. The didodecahedron may be obtained in a similar manner. The hemihedral forms of these solids are of course deduced in the same manner as the holohedral. The cause of their occurrence in general we have already explained.

In the fourth, or trimetric system, where the crystallographic axes intersect at right angles, and are all unequal, the molecule is evidently an ellipsoid. If the poles are situated at the extremities of the axes of this ellipsoid, the form produced will be a prism with a rectangular base. As the poles are unlike, it is evident that cleavage may exist in such a form parallel to any of the faces. There is, however, another cleavage, namely, parallel to all the lateral faces of a prism, having a rhomboidal base; and this will arise if the lateral poles are situated at the extremities of equal conjugate diameters. DANA has explained the formation of both these prisms.

The secondary forms can be easily deduced in a manner precisely analogous to that in which we have deduced those of the other systems.

The formations of the two remaining systems take place in precisely analogous ways. To enter into an explanation of all the combinations could only prove tedious. I shall, in conclusion, show that the phenomena of hemitrope forms and twin crystals are in strict accordance with, and can be readily explained by, the hypotheses which I have advanced; and further, that some of them can be explained on these views, which were quite unintelligible on DANA's hypothesis.

One of the best known cases of hemitropism in the first system is where one half of an octahedron is rotated on another, through an angle of 180° , the plane of separation being parallel to an octahedral face. Such combination is

found in crystals of spinel, a mineral in which the cleavage is octahedral. We must, accordingly, show how it may take place, on the hypothesis which explains the octahedral formation. A plane joining the three poles A, B, C, (Fig. 10) is evidently parallel to a face of the octahedron of which the molecule forms a part. Hence, if two such molecules be united by two points equidistant from three such poles, they will each become the origin of a crystal; and since they will naturally assume a symmetrical position with regard to each other, A opposite A', &c., these two crystals, of which they are the origin, will be *similarly* situated. Also, since each crystal prevents the other from growing, except in a direction away from itself, they will together make up only one crystal. Thus, the halves of *two* crystals similarly situated are evidently the same as the halves of the same crystal rotated on each other through 180° .

Crystals are also found in which the cleavage is octahedral, and composition has taken place parallel to a face of the cube: such are some crystals of diamond. These forms will result if two molecules, such as in the last case, unite at a point of equilibrium between *four* poles. We have seen that the dodecahedron of the first system may be built up of molecules having eight poles; and I have stated that the molecules, as they unite, will occupy such a relative position that the poles will be disposed symmetrically. Although that is unquestionably the normal position of equilibrium, yet there is evidently another position in which two such spheres may unite by two poles, namely one 180° remote from this. Such is a position of unstable equilibrium; but it is one which, if nothing occurs to destroy it, will become the basis of a crystal. Two such molecules will be the germs of two crystals, which, from the peculiar circumstances under which they are formed, together exhibit the parts of one crystal: they will be united by a plane parallel to a face of the octahedron, and will exhibit the dodecahedral cleavage. Crystals of blende are found of this formation. We might also have two such spheres united by two points intermediate to four poles, the lines joining which would form a face of a cube; and if these molecules became the centres of formation, we would have a crystal with dodecahedral cleavage, and hemitropism on a cubic face. Such a crystal, however, could not be distinguished by the eye from an ordinary cube. In fact, there are certainly twelve positions in which two such molecules might unite and be in equilibrium. The question is then merely one of probability as to which combination may most readily take place. Those combinations which

we have mentioned are clearly the most likely to happen, and they are those which have been found in nature.

Cases in which hemitropism has occurred, and where the crystal has cubical cleavage, have been already explained by DANA. As, however, his theory could not account for the octahedral or dodecahedral formation, it could not possibly show how such crystals might be subject to hemitropism. I trust that I have shown that the theory which I have put forward is not wanting as regards this test.

In Fig. 19 is given a representation of a crystal of spinel in which composition has taken place parallel to two octahedral faces. Fig. 20 represents a dodecahedron in which composition has taken place parallel to an octahedral face. These may be taken as instances of twin formation, where the parts together make up only one crystal. There is, however, another description of crystals which have been generally placed in the same category, namely, those in which the complete parts of two crystals appear. There does not seem to be any reason why these should be classed as twin crystals at all, except to preserve the rule that simple crystals are never found with re-entrant angles. In Figs. 21, 22,* instances of this sort of formation are shown; they can evidently be explained on the very same principle of decrements as all other secondary forms. These hemitrope forms are known to be very numerous: to enumerate all of them would be both tedious and unnecessary. I shall content myself with one example illustrative of the cases in which DANA's hypothesis fails, and where it is necessary to suppose the existence of twelve poles. In Fig. 23 is shown a crystal of copper pyrites, which evidently consists of six octahedra united by their extremities. It is not possible to conceive how six of DANA's molecules could unite in this manner; but it will readily take place when the poles are disposed as shown in Fig. 16, the four poles at the extremities of the molecule uniting in this position. It is also to be remarked, that the cleavage in this case is octahedral.

On a subject so vast much must remain unsaid; but I trust that, although I may not have reviewed every case, there is no important class of phenomena which cannot be brought under the hypotheses which I have advanced.

* These figures have been taken from the first volume of BREWSTER's "Edinburgh Journal," where they are appended to a most able Paper on Twin Formation, by HAIDINGER.